CALIBRATION AND DATA CORRECTION TECHNIQUES FOR SPECTRAL GAMMA-RAY LOGGING

by

David C. Stromswold

and

Robert D. Wilson

Bendix Field Engineering Corporation

Grand Junction, Colorado 81502

ABSTRACT

Calibration techniques are presented for spectral logging of ^{40}K, ^{214}Bi (a decay product of uranium), and ^{208}Tl (a decay product of thorium) using scintillation detectors. Methods of correcting field data for steel casings and water in boreholes are described along with typical correction factors. Spatial deconvolution parameters for restoring the character of logs at zone changes are discussed both for the iterative technique of GAMLOG based on half-foot anomalies and for the inverse filter technique that uses the exponential fall-off of signals from thin zones of ore. A short description of the U.S. Department of Energy's calibration facility at Grand Junction, Colorado is also given as it pertains to spectral calibration and data correction activities.

INTRODUCTION

As part of its work for the United States Department of Energy (DOE), Bendix Field Engineering Corporation (BFEC) has developed spectral gamma-ray logging hardware and data handling techniques. Calibration of the equipment and correction of the data for borehole and formation effects are two important steps in using logging data to assay for uranium. Procedures for calibrating spectral systems using scintillation detectors are described in the following sections.

Calibration is based on observed count rates in models of known concentration of potassium, uranium, and thorium. The following energy gamma rays are used to identify these elements: 1.46 MeV from ^{40}K, 1.76 and 2.20 MeV from ^{214}Bi (a decay product of uranium), and 2.61 MeV from ^{208}Tl (a

decay product of thorium). Counts from these gamma rays are recorded for three energy windows which span the intervals shown in Table 1.

Table 1. Spectral Energy Windows.

Identification	Energy Window (keV)
Potassium	1320-1575
Uranium	1650-2390
Thorium	2475-2765

Sodium iodide crystals are used in the probes to detect gamma rays. For logging in low count-rate formations, large (1.5-inch x 12-inch), unfiltered detectors are used, and in regions of higher count rates, data are collected with small (1-inch x 6-inch), filtered detectors. Both detectors are contained in the same probe and selection of the detectors is performed remotely during logging. It is standard BFEC/DOE procedure to start with the large detector and switch to the small detector only after the large detector gives a count rate greater than 1500 counts per second above an energy threshold at 1250 keV. The small detector is thus used on repeated sections of holes when demanded by excessive count rates in the large detector.

Signals from the detectors are shaped and amplified within the probe and sent analog up the logging cable. Uphole the signals are reshaped, amplified, and gain stabilized to provide a constant pulse height for the manganese reference pulses at 835 keV. Spectral discrimination is obtained by either single-channel analyzers or a multichannel analyzer. Gamma-ray counts in the potassium, uranium, and thorium windows are accumulated and then recorded on magnetic tape along with the depth of the probe in the hole. A logging speed of 5 feet per minute is generally used, and data are recorded at 0.5-foot increments along the hole.

MODELS

The efficiency of detectors used in logging must be determined in distributed radioactive sources sufficiently large so as to appear to be infinite. In practice this can be accomplished by having the sources extend approximately 2 feet in every direction from the detector. Such sources are often constructed as cylinders of concrete mixed with radioactive elements. The concrete approximates the density (≈ 2 g/cm^3) of the rock in which logging

is to be performed, and the cylinders have holes along their axes for probe insertion. Extended-source models in cylinders having 4-foot diameters are available at Grand Junction and selected field sites.

The primary spectral standards are located at Grand Junction, and they are designated as the potassium (K), uranium (U), and thorium (Th) models. Additional models are available for determining spectral water correction factors; these models are the KUT water model (KUT WTR) and the D model. The grades assigned to these models are given in Table 2. Background measurements are made in a large water tank to reduce the effect of natural radioelements in the calibration area. The concentrations of potassium, uranium, and thorium in the water tank are small and considered to be zero for probe calibration.

Table 2. Grades of Models.

Model	% K	ppm U	ppm Th
Potassium	6.76 ± 0.18	2.7 ± 0.3	2.4 ± 0.6
Uranium	0.84 ± 0.24	498.3 ± 12.1	5.6 ± 1.3
Thorium	1.44 ± 0.08	28.3 ± 1.0	505.5 ± 12.1
KUT WTR	4.90 ± 0.29	321 ± 19	219.4 ± 9.2
D	1.78 ± 0.26	576 ± 76	7.7 ± 1.7

Data collected from thin beds of radioactive elements must be processed to remove the averaging effects inherent in logging. Sharp ore/barren transitions can be partially restored if the spatial response of the detector is known. Special thin-bed models are available at Grand Junction for determining the response of detectors to thin uranium beds. These models have 2-inch-thick concrete zones with 0.246 percent eU_3O_8 and are positioned at several angles with respect to a central borehole. The spatial response of a detector can also be determined in calibration models with thick ore zones by logging the interfaces between ore zones and barren zones.

COLLECTION OF CALIBRATION DATA

The gain of the spectral system must be properly adjusted so that the gamma-ray peaks fall in their correct locations for proper identification. This is usually done using a thorium source after the system has warmed up sufficiently (approximately 20 minutes) and the gain stabilizer has been

centered on the reference peak from manganese. At a minimum, the 2614 keV peak from the thorium source must occur in a pre-established location in the multichannel analyzer. An improved procedure is to calibrate the multichannel analyzer for gain using the 583 and 2614 keV gamma rays from a distributed thorium source. Once this has been done, the window locations can be checked against their desired positions (Table 1). The use of the 835 keV gamma ray from the manganese stabilization source for energy calibration is not recommended. The apparent energy of this gamma ray changes as the source is moved along the length of the crystal due to nonlinearities in the detector's light output. It is best to use a distributed source for energy calibration.

Before and after calibrating a probe in the models, it is customary to record window count rates from a "field calibrator" source made of thorium ore packed in a tube (approximately 2 inches thick x 12 inches long). The observed count rates after local background has been subtracted are used later to test probe operation in the field. Unfortunately some probe malfunctions may not be detected from this test. Observation of the gamma-ray spectra on the multichannel analyzer provides better understanding of the probe's condition.

The counting efficiency of a detector is determined by recording counts in the potassium (K), uranium (U), and thorium (Th) models at a detector depth of 5.5 feet. The K model provides the lowest count rates of all the models, and thus it requires longer counting times than both the U and Th models in order to obtain equivalent counting statistics. Background counts are obtained by placing the probe in a large water tank with the detector at a depth of 5.5 feet. The times needed for collection of adequate data also vary with detector volume and shielding (filters). Counting times used in calibrating Bendix/DOE spectral probes in the models are given in Table 3.

Table 3. Calibration Counting Times.

Detector Volume	Typical Detector	Counting Time (seconds)			
V (in^3)	Size (inches)	K Model	U Model	Th Model	Background
$15 \leq V < 25$	1.5 x 12	3000	2000	2000	4000
$5 \leq V < 15$	1.5 x 3	4500	3000	3000	5000
$2 \leq V < 5$	1 x 6 Filtered	6000	4000	4000	5000

ANALYSIS OF CALIBRATION DATA

The calibration data needed are the counts and counting times for the three energy windows in the K, U, Th, and background models. These data are used in a computer program which determines sensitivities and stripping coefficients based on assigned grades of the models. The program uses linear equations to determine proportionality constants that relate window count rates to model concentrations after background count rates have been subtracted. In a matrix formalism the relationship is

$$R = AC \tag{1}$$

where

R = 3 x 3 matrix of observed count rates in K, U, and Th models after background has been subtracted;

C = 3 x 3 matrix of concentrations of calibration models;

A = 3 x 3 matrix of proportionality determined from R and C.

The elements of the three matrices are defined as follows:

R_{ij} = count rate in ith energy window in the jth calibration model after background subtraction;

$C_{\ell j}$ = concentration of ℓth radioactive element in jth calibration model;

$A_{i\ell}$ = constant relating count rate in ith energy window with concentration of ℓth radioactive element.

The matrix expression in equation (1) can be written in terms of its individual elements as

$$R_{ij} = \sum_{\ell=1}^{3} (A_{i\ell} C_{\ell j})$$

The convention used in defining the subscripts is:

1 = Potassium

2 = Uranium

3 = Thorium.

Thus, for example, R_{13} is the count rate in the potassium energy window obtained in the thorium calibration model after background subtraction.

The analysis program calculates the proportionality matrix A, its matrix inverse A^{-1}, and the uncertainties in the A and A^{-1} matrix elements. The uncertainties are determined from propagation of the counting statistics in the window counts and the uncertainites in the assigned grades of the calibration models (Stromswold and Kosanke, 1978).

Concentrations of K, U, and Th in the field where logging data are collected are calculated using the matrix equation

$$C = A^{-1}R \tag{2}$$

where

C = 3 x 1 matrix of concentrations to be calculated

A^{-1} = 3 x 3 matrix of proportionality from calibration models

R = 3 x 1 matrix of field count rates (logging data).

Equation 2 can be written in terms of its matrix elements as

$$C_i = \sum_{\ell=1}^{3} (A^{-1}_{i\ell} R_\ell)$$

where

C_i = concentration of ith radioactive element

$A^{-1}_{i\ell}$ = $i\ell$ matrix element of A^{-1}

R_ℓ = count rate in ℓth energy window after background subtraction.

The background count rates which are subtracted from field data are taken to be those determined during calibration in the water tank. These values should be acceptable because most of the background is generated by the manganese stabilization source through chance coincidences in which the energies add to reach the spectral windows.

CORRECTIONS TO FIELD DATA

Data collected in the field must be corrected for conditions different from those under which the calibrations were performed. Two significant borehole conditions for which corrections must be made are the variation of fluid-filled hole diameter and the presence of steel casing.

Water

Corrections for water in holes of various diameters are determined experimentally using the KUT water factor and D calibration models. Count

rates are collected with the detector in these models for the holes both dry and water-filled. The data are analyzed to determine apparent concentrations of K, U, and Th for the holes wet and dry based on a calibration of the detector in the dry, 4.5-inch holes of the K, U, and Th calibration models.

Water correction factors are determined from the ratio of the calculated concentrations for the wet and dry holes:

$$\text{Water Correction Factor} = \frac{\text{Calculated concentration, dry}}{\text{Calculated concentration, wet}}$$

Separate correction factors are determined for K, U, and Th and they are used to multiply the (uncorrected) concentrations of these elements calculated from field logging data:

Corrected Field Concentration = (Uncorrected Field Concentration) x (Water Correction Factor).

Separate correction factors must be determined for centralized and sidewall positions of the probe within the hole. Unless there is a mechanical centering device, such as a three-arm caliper, it is customary to assume that the probe rests against a side of the borehole during logging. The sidewall and centralized water correction factors have fundamentally different variations with hole size. The sidewall factors approach a limiting value at large hole diameters, whereas the centralized water factors increase without limit at large diameters.

The process of correcting for water in the holes only adjusts the sensitivities of a probe to K, U, and Th. The effect of the water on spectrum shape is not fully incorporated in these corrections because the calibration models presently available are not sufficient to provide data on corrections in addition to changes in the sensitivity factors. The error made by ignoring these additional considerations has been estimated, however, from experimental data for 4.5-inch holes and calculated (Evans, 1980) from theoretical considerations for holes up to 12 inches in diameter. Changes in spectrum shape are reflected by changes in stripping ratios, and for the 4.5-inch hole, the experimental stripping ratios changed by less than 2 percent from wet to dry holes. The calculated stripping ratios for a sidewalled probe changed by less than 8 percent for holes from 3 to 12 inches in diameter. For a

centralized probe, the stripping ratios changed by less than 13 percent for the same range of hole diameters. Most uranium logging is performed in the sidewall mode in holes of diameter 7 inches or less. For these situations, the calculated variation in stripping ratios is less than 5 percent, and disregard of such variations should produce acceptably small errors in calculated concentrations from logging data.

The water correction factors for sensitivity to K, U, and Th have been determined experimentally using large, unfiltered detectors, and the resulting correction factors are shown in Figure 1 for the centralized condition and in Figure 2 for the sidewalled configuraton. The potassium corrections were measured in the upper barren zone of the D model, the uranium corrections in the ore zone of the D model, and the thorium corrections in the ore zone of the KUT water model. The technique of using different sections of the models for the three correction factors has proven to give better results than using just one location because it minimizes stripping problems.

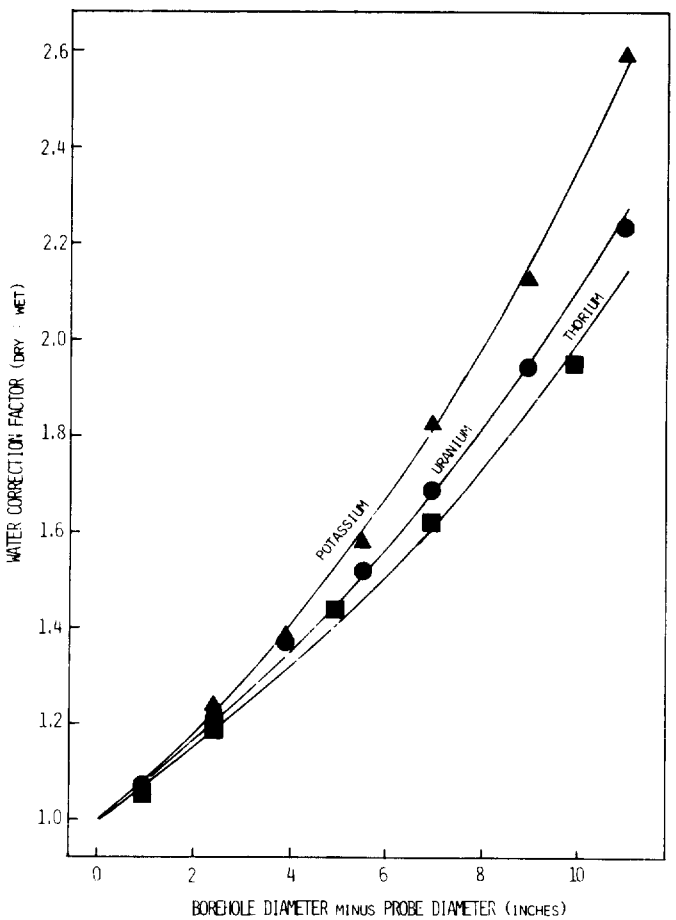

Figure 1. Water correction factors for KUT sensitivities with probe centralized in hole.

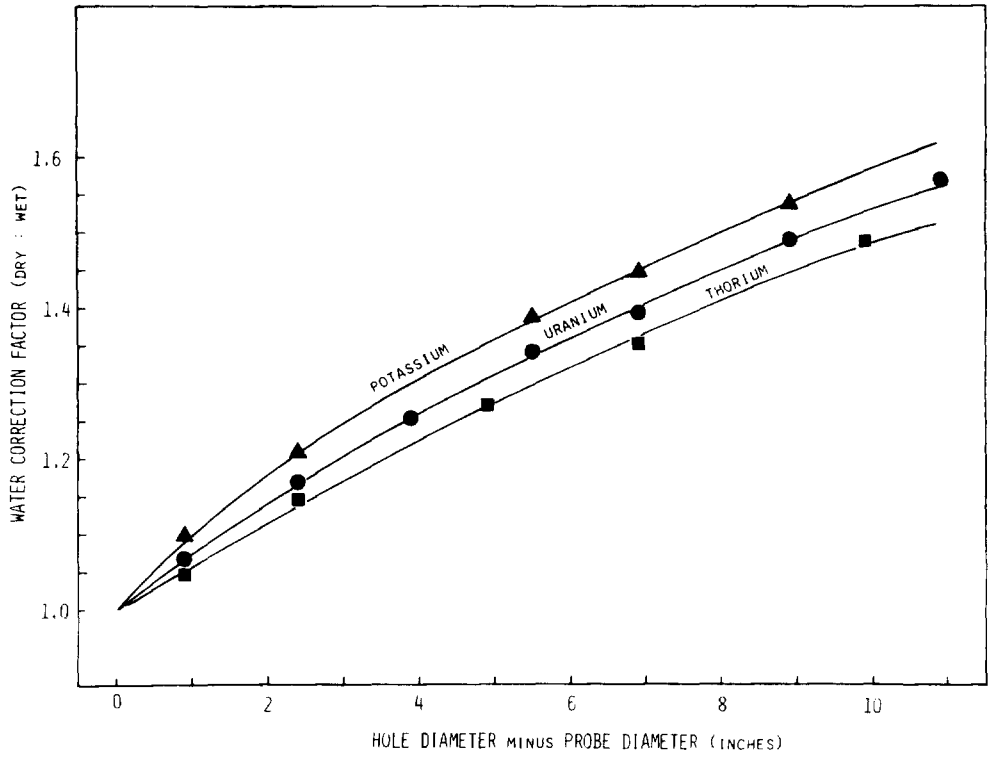

Figure 2. Water correction factors for KUT sensitivities with probe sidewalled in hole.

The correction factors in Figure 1 and 2 are plotted as a function of hole diameter minus probe diameter. The suitability of this parameter for a sidewalled probe was tested experimentally for thorium by placing PVC sleeves (with their bottom ends closed) around a probe to simulate different probe diameters. The results are shown in Figure 3. Although there is some variation in the correction factors shown, it is apparent that using hole diameter minus probe diameter as a water correction parameter is acceptable for sidewall correction factors. Using the same parameter for centralized probes is clearly correct from theoretical considerations.

The water correction data for a 1.5 x 12-inch NaI(Tl) detector in a 2.1-inch, centralized probe (Figure 1) have been fitted to the exponential curve

$$\text{Water Correction (centralized)} = c \cdot \exp(dx)$$

where

x = hole diameter minus probe diameter (inches)

c, d = fitting constants given in Table 4.

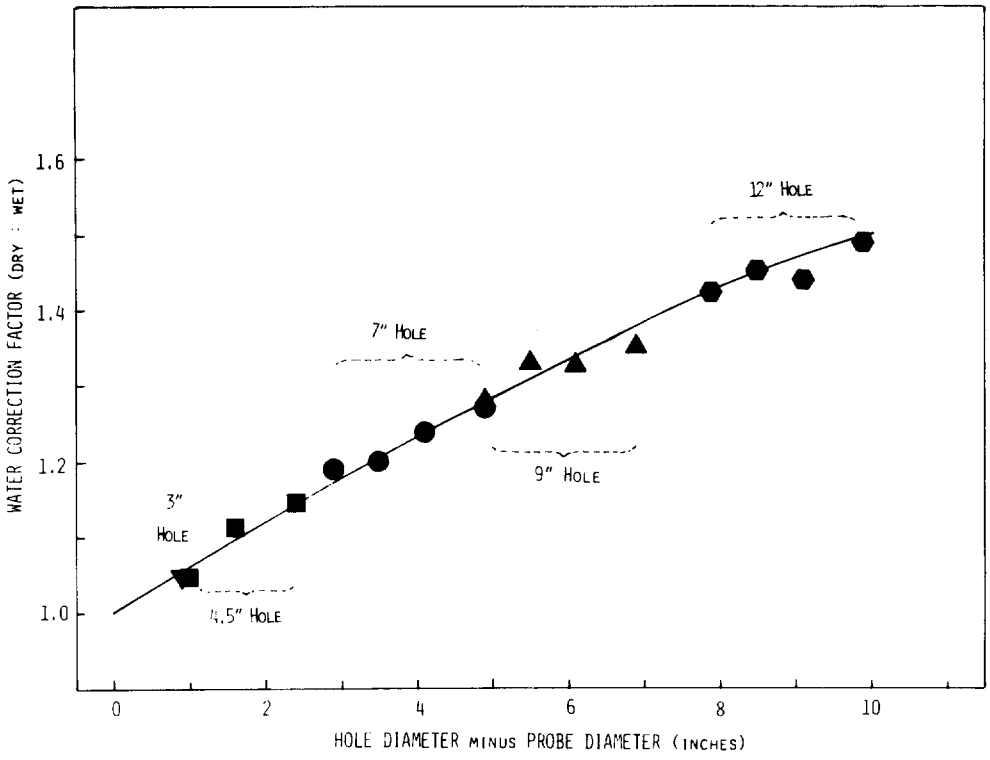

Figure 3. Thorium water correction factors for simulated probe diameter changes using PVC sleeves.

Table 4. Fitting Constants for Centralized Water Corrections.

Elements	c	d
Potassium	0.9912	0.0872
Uranium	1.0116	0.0737
Thorium	1.0031	0.0688

The correction data in Figure 2 were obtained using a 1.5 x 9-inch NaI(Tl) detector in a 2.1-inch diameter probe, and the data have been fitted to a power correction curve:

$$\text{Water Correction (sidewall)} = 1 + ax^b$$

where

x = hole diameter minus probe diameter (inches)

a, b = fitting constants whose values are given in Table 5.

Table 5. Fitting Constants for Sidewall Water Corrections.

Elements	a	b
Potassium	0.1090	0.7375
Uranium	0.0777	0.8484
Thorium	0.0561	0.9662

Steel Casing

The presence of steel casing reduces the number of formation gamma rays reaching a detector in a borehole, and corrections must be made to obtain correct concentrations from the logging data obtained in cased holes. Steel casings of thickness 0.06-inch to 0.5-inch are available at Grand Junction for determining casing corrections experimentally. These casings have an inside diameter of 3 inches and they are 4.5 feet long. They are hung individually over a detector and counts are recorded in the K, U, and Th calibration models. In this way, a separate calibration is obtained for each casing thickness, and changes in both sensitivities and stripping ratios can be calculated.

The effect of steel casing is applied to field data by adjusting the calibration matrix, A^{-1}, prior to calculating concentrations from the logs. The steel casing correction factors, F_{ij}, are used to adjust the elements of the A^{-1} calibration matrix as follows:

$$A^{-1}_{ij} \text{ (cased)} = A^{-1}_{ij} \text{ (uncased)} \times F_{ij} .$$

The functional form of F_{ij} is taken as

$$F_{ij} = \exp (f_{ij} \, x)$$

where

f_{ij} = fitting parameter

x = number of 0.625-inch thicknesses of casing.

Values of f_{ij} obtained for a 1.5-inch x 12-inch NaI(Tl) detector in a probe having a shell thickness of 0.125-inch are given in Table 6.

Table 6. Steel Casing Parameters for 1.5-inch x 12-inch NaI(Tl) Detector.

Parameter	Value
f_{11}	0.072
f_{12}	0.075
f_{13}	0.083
f_{21}	0.000
f_{22}	0.068
f_{23}	0.075
f_{31}	0.000
f_{32}	0.037
f_{33}	0.058

Background Subtraction

There is generally very little background in the K, U, and Th windows which needs to be subtracted from field data. The background counts that do appear come mainly from the manganese stabilization source which emits gamma rays of energy 835 keV. The simultaneous arrival of two manganese gamma rays in the detector can produce a summed pulse which reaches the K or U windows.

The background count rates obtained in the water tank during probe calibration can be used for subtracting background from field data. These count rates, which include the effects of the summed manganese contributions, will decrease with the square of the source count rate as the source decays during its 312-day half life. Backgrounds measured within 2-3 months of field logging should be adequate for most purposes.

No correction is made for pile-up of a manganese gamma ray with a formation gamma ray. Such a correction would be difficult to determine because it varies with formation count rate as well as manganese source strength.

SPATIAL DECONVOLUTION

The process of logging a formation often provides an inaccurate representation of the spatial distribution of radioactive materials, especially when the formation contains thin zones of ore. The log shows a general representation of the ore's distribution, but sharp zone changes are washed out and

appear on the log as gradual transitions. The data can be deconvolved spatially to produce a better representation of the formation if the response of the detector to thin zones is known. This response can be measured directly in calibration models such as the thin-bed models, or it can be calculated from logging data collected in thick-zone models which have a sharp transition between an ore zone and a barren zone.

Two techniques for spatially deconvolving gamma-ray logs have been used: GAMLOG, which deconvolves using a series of half-foot weighting coefficients, and the inverse digital filter based on an exponential fall-off of the signal from thin zones. Data were collected in the calibration models to determine spatial deconvolution parameters for a 1.5-inch x 12-inch NaI detector and a filtered 1-inch x 6-inch NaI detector in a 2.1-inch diameter probe having a 0.1-inch thick steel wall.

GAMLOG

In the GAMLOG technique (Scott, 1963), an iterative procedure is used to calculate a series of 0.5-foot-thick anomalies. Weighting factors for 0.5-foot intervals comprise a symmetric five-point filter which is passed over the logging data to sharpen the log's transitions between zones of differing ore grades. The weighting factors can be determined experimentally for the uranium energy window using the 90° bed of the thin-bed calibration model. The simulated half-foot anomaly needed for GAMLOG can be obtained from the 2-inch-thick zone data from the thin-bed model by summing logging data from three adjacent 2-inch zones. When this was done for a 1.5-inch x 12-inch detector, the data in Figure 4 were obtained for a simulated half-foot anomaly. The data in the figure have already had background subtracted as determined in the barren portion of the model far from the ore zone. The curve drawn through the data is a visual fit to the points. GAMLOG weighting coefficients can be determined from the relative counting rates at 0.5-foot intervals from the peak at the center of the simulated ore zone. Resulting coefficients are listed in Table 7 for the case with the borehole dry and water filled (as in Figure 4). Weighting coefficients are also listed for the filtered 1-inch x 6-inch detector with the borehole dry. Notice that the coefficients for the 1-inch x 6-inch detector fall off more rapidly from the center value than do the ones for the 1.5-inch x 12-inch detector. This is in

agreement with expectations that a long detector will have a more spread out spatial response to a thin zone than will a short detector. The addition of water to the 4.5-inch borehole had little effect on the weighting coefficients for the 1.5-inch x 12-inch detector.

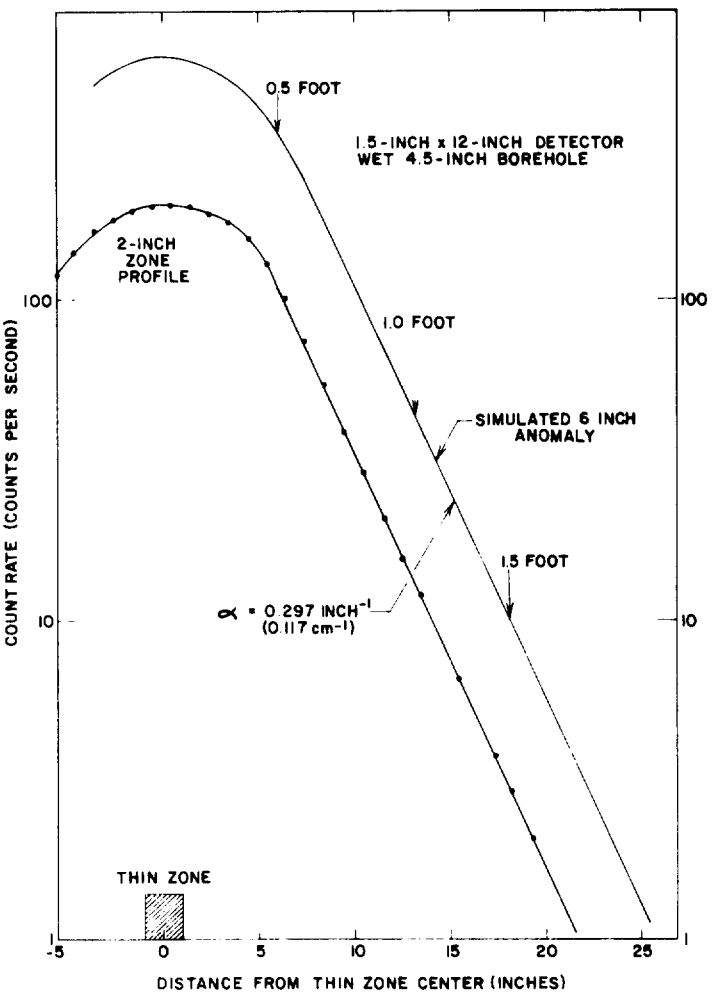

Figure 4. Spatial response of a detector to a 2-inch-thick uranium zone (lower curve) and derived response for 6-inch-thick uranium zone (upper curve).

Table 7. GAMLOG Weighting Coefficients for Uranium Window.

	Hole	Distance (feet)			
Detector	(4.5-inch)	0.0	0.5	1.0	1.5
1.5 x 12	Dry	1.000	0.570	0.108	0.020
1.5 x 12	Wet	1.000	0.573	0.105	0.018
1 x 6 filtered	Dry	1.000	0.365	0.060	0.010

The coefficients in Table 7 must be normalized to their sum so that they do not affect the grade-thickness product of the log. For example, the values for the 1.5-inch x 12-inch detector in the dry hole must be divided by 1.000 + 2(0.570) + 2(0.108) + 2(0.020) = 2.396 to obtain proper normalization. In addition, the coefficients listed are only for the uranium energy window, but in the absence of thin bed models for determining weighting coefficients for potassium and thorium, the values in Table 7 are assumed to be approximately correct for K and Th also.

Inverse Filter

A second method of spatially deconvolving gamma-ray logs is the inverse digital filter technique (Conaway and Killeen, 1978). This is a noniterative method which assumes that the response of a point-sized detector to an infinitesimally thin zone is the double-sided exponential

$$I(z) = \frac{\alpha}{2} \exp(-\alpha|z|)$$

The constant alpha (α) depends on several factors including borehole diameter and fluid content, and z is the distance from the detector to the thin zone.

Values of alpha can be determined from thin zone models directly or by differentiating the count rates obtained from logging an interface between thick zones of a model having a large grade difference. The differentiation produces a hypothetical count rate profile that would be observed from an infinitesimally thin ore zone located at the interface between the two thick zones. When the profile is plotted on semilogarithmic paper, the slope of the curve gives the value of alpha (Conaway, 1980).

Data from the thin-bed model were used to determine alpha for the 1.5-inch x 12-inch and filtered, 1-inch x 6-inch detectors. After plotting background subtracted count rates on a semilogarithmic graph, the data which fell along straight lines were entered in an exponential curve fitting routine to determine alpha. In this way, tails of the curves which departed from an exponential relationship were avoided, and possibly better values of alpha were obtained than would have been determined from strictly graphical methods.

Resulting values of alpha are given in Table 8 for the uranium energy window. In the absence of suitable thin bed models for K and Th, these same values are used for K and Th also.

Table 8. Alpha Parameters from Thin-Bed Model.

Detector	Hole (4.5-inch)	Alpha in^{-1}	Alpha cm^{-1}
1.5 x 12	Dry	0.286	0.113
1.5 x 12	Wet	0.297	0.117
1 x 6 filtered	Dry	0.299	0.118

The variation of alpha with hole diameter was determined from data collected in the D Model using a 1.5-inch x 7-inch NaI(Tl) detector in a 2.6-inch-diameter probe having a 0.1-inch-thick steel shell. Logging data were collected across the ore zone/barren zone interface in holes of diameter 3 to 11 inches for both dry and water-filled conditions. The values of alpha obtained are given in Table 9 and plotted in Figure 5. At small hole diameters (4.5 inches and less), the alphas show little significant difference between the wet and dry holes. However, for the larger holes, alpha is distinctly smaller when the holes are dry. The smaller alphas imply that the signal from a thin zone falls off less rapidly in air than it does in water. The decreased fall off in air is reasonable from attenuation considerations applied to gamma-ray propagation through the air or water of the borehole.

Table 9. Alpha Parameters for 1.5-inch x 7-inch NaI Detector.

Hole Diameter (inches)	Alpha (in^{-1}) dry	Alpha (in^{-1}) wet	Alpha (cm^{-1}) dry	Alpha (cm^{-1}) wet
3	0.338	0.346	0.133	0.136
4.5	0.298	0.301	0.117	0.118
6	0.261	0.276	0.103	0.109
9	0.214	0.262	0.084	0.103
11	0.196	0.244	0.077	0.096

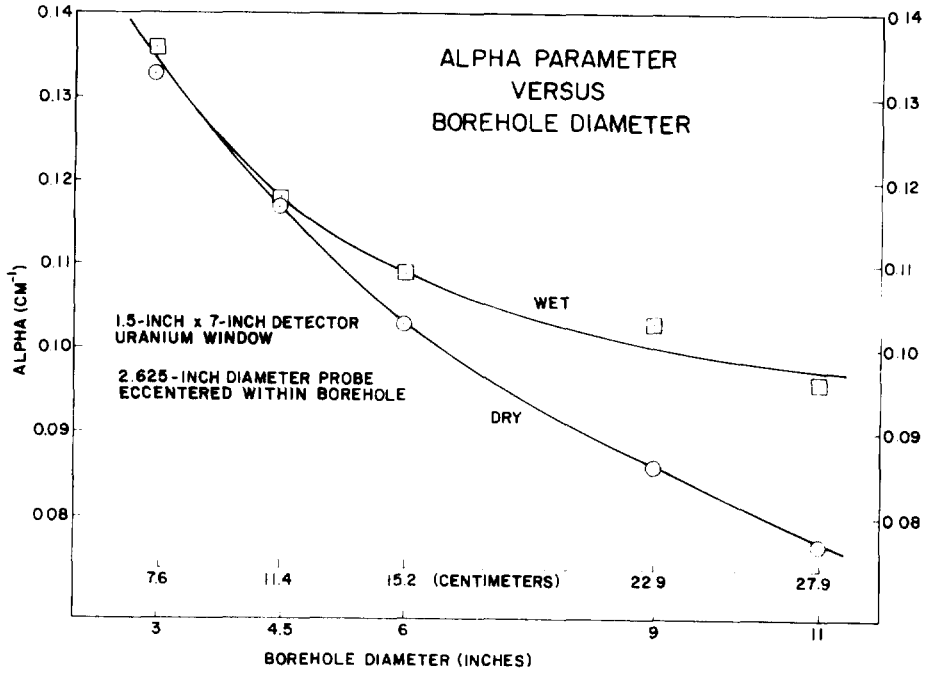

Figure 5. Variation of spatial deconvolution parameter alpha with hole diameter for dry and water-filled holes.

CONCLUSION

The K, U, and Th models at Grand Junction are the primary standards used in calibrating Bendix/DOE spectral probes. Data collected in these models are analyzed in a matrix technique to determine counting efficiencies and spectrum stripping parameters for potassium, uranium, and thorium. The calibrations are applied to spectral data collected in the field to obtain apparent potassium, uranium, and thorium concentrations. The resulting concentrations can be corrected for the presence of borehole water and casing by the application of multiplicative correction factors. Typical water correction factors for both centralized and sidewall geometries have been presented.

Spatial deconvolution techniques can be applied to logging data to help restore the appearance of sharp bed boundaries and thin ore zones. Experimental deconvolution coefficients have been presented for both the iterative deconvolution procedure of GAMLOG and the alpha values of the inverse digital filter method.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy through Contract No. DE-AC13-76GJ01664.

REFERENCES

Conaway, J. G., 1980, Direct determination of the gamma-ray logging system response function in field boreholes: Geoexploration, v. 18, p. 187-199.

Conaway, J. G. and P. G. Killeen, 1978, Quantitative uranium determinations from gamma-ray logs by application of digital time series analysis: Geophysics, v. 43, p. 1204-1221.

Evans, M. L., 1980, Private communication of gamma-ray transport calculations performed at Los Alamos Scientific Laboratory.

Scott, J. H., 1963, Computer analysis of gamma-ray logs: Geophysics, v. 28, p. 457-465.

Stromswold, D. C. and K. L. Kosanke, 1978, Calibration and error analysis for spectral radiation detectors: IEEE Transactions on Nuclear Science, Vol. NS-25, p. 782-786.

ABOUT THE AUTHORS

David C. Stromswold received his Ph.D in physics from the Johns Hopkins University in 1976. At Bendix he is involved in technology development for uranium exploration using scintillation and high resolution gamma-ray detectors.

Robert D. Wilson received his Ph.D. in engineering physics from the University of Virginia in 1973. He is presently the leader of the gamma-ray logging R&D group at Bendix.